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# Energy Supply Modelling of a Low-$CO_2$ Emitting Energy System: Case Study of a Danish Municipality[i]

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## Abstract

Municipal activities play an important role in national and global $CO_2$-emission reduction efforts, with Nordic countries at the forefront thanks to their energy planning tradition and high penetration of renewable energy sources. In this work, we present a case study of the Danish municipality of Sønderborg, whose aim is to reach zero net $CO_2$ emissions by 2029. Sønderborg has an official strategic plan towards 2029, which we compared with four alternative scenarios to investigate how the municipality could approach its target in the most energy-efficient and cost-effective way while simultaneously keeping biomass and waste consumption close to the limits of the locally available residual resources.

We modelled all sectors of the energy system on the municipal scale, applying a broad range of energy conversion technologies, including advanced biomass conversion technologies and reversible electrolysis. We constructed five scenarios, each representing a different energy mix for Sønderborg's energy system in 2029. We modelled these scenarios using the mixed-integer linear optimization tool Sifre. We compared the results for the five scenarios using four indicators: annual total system cost, total energy system efficiency, annual net system $CO_2$ emissions and total annual biomass consumption.

The results show that scenarios with a high degree of electrification perform better on the selected indicators than scenarios with a high degree of biomass utilization. Moreover, the incorporation of advanced conversion technologies such as electrolysis, fuel cells and methanol production further reduces both the total system cost and net $CO_2$ of the highly electrified energy system. Our sensitivity analysis demonstrates that scenarios with a low biomass consumption and a high degree of electrification are less dependent on changes in energy prices.

We conclude that in order to achieve their $CO_2$ emission goals in the most energy-efficient, cost-effective and sustainable way, municipalities similar to Sønderborg should compare a wide range of

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energy system configurations, for example, scenarios with a high degree of electrification and a limited biomass use.

## Highlights

- Urban energy system scenarios for Sønderborg, Denmark
- Keeping biomass consumption within the limits of the locally available resources
- Lowest cost and $CO_2$ emissions by using heat pumps, solar heating and electrolysis


## Keywords

energy system modelling; urban energy scenarios; renewable energy; mixed-integer linear optimization; energy conversion; electrolysis


## 1 Introduction

Energy policy and $CO_2$ reduction targets on the municipal level play a significant role in the national $CO_2$ reduction efforts in most countries, being of global importance in the transition to a more sustainable energy supply. Municipal energy planning has gained increased attention in recent years [1–3]. In the EU, initiatives such as Covenant of Mayors encourage exchange of experience among cities working with sustainable energy [4]. In particular, Scandinavia is one of the most experienced regions in strategic energy planning. Following the oil crises in the 1970s non-obligatory energy plans were implemented in Sweden [5] and heat supply plans introduced in Denmark [6]. Currently, most Danish municipalities have issued some climate action plans [7] and declared future $CO_2$ goals, for example Copenhagen [8], Aalborg [9] and Helsingør [10].

In this paper, the Danish municipality of Sønderborg has been selected as a case study of municipal energy supply planning. Sønderborg has a population of about 75,000, located on the Jutland peninsula and the island of Als in southern Denmark (see Figure 1). In 2009 Sønderborg set itself the target of becoming $CO_2$-neutral by 2029 [11]. According to the municipality's plans, the target is to be reached by replacing gas-fired turbines and boilers with wind turbines, heat pumps, biomass boilers and solar heating, and by replacing the natural gas supply with locally produced biogas. In Sønderborg's plans, $CO_2$ neutrality is understood as achieving net zero $CO_2$ emissions by balancing remaining $CO_2$ emissions in the region with an equivalent amount of emissions offset, for example, by exporting energy from low-carbon sources out of the municipality. We use the same definition in this study.

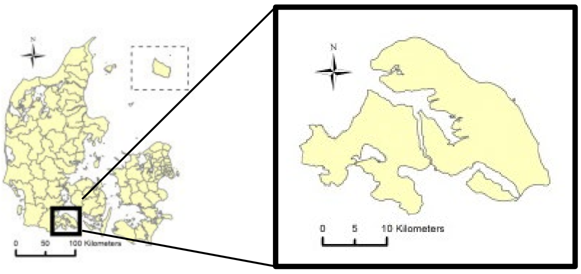


**Figure 1.** Location of Sønderborg municipality, Denmark.

This ambitious energy policy makes Sønderborg a highly interesting case. The municipality is very active in realizing its policy and has received funding from several EU and Danish grants to do so. Sønderborg also runs an internal initiative called Project Zero [12], which has provided us with valuable data and validation of our assumptions during this work. In terms of scale, Sønderborg represents a middle-sized Scandinavian municipality with an energy system small enough to make possible a detailed case study, yet complex enough to represent a full urban-scale energy system. The main findings of the case study should therefore be easily applicable or transferable to other similarly sized northern European cities.

Sønderborg municipality's existing strategic energy plan [11] describes the measures the municipality proposes to take to reach its 2029 emission target. The expected results of the plan in 2029 are presented in [11] and favorably compared with a "business as usual" scenario, though no alternative scenarios with different energy supply mixes are investigated. Therefore the plan does not focus on the question of whether Sønderborg's proposed measures are the most suitable pathway towards the municipality's emission target, or whether other, more socio-economically cost-effective and energy efficient pathways for reaching the target could be pursued. Moreover, the strategic energy plan does not address how the amount of biomass consumed for energy purposes in Sønderborg is expected to compare with the locally available residual biomass resources in 2029. To address these issues, in this paper we have developed and analyzed four alternative scenarios for the state of Sønderborg's energy system in 2029 and compared them with the municipality's plan.

In Denmark, as elsewhere, many energy producers currently plan to reduce their greenhouse gas emissions by combusting wood chips or wood/straw pellets instead of fossil fuels in combined heat and power plants. However, if these plans were all to be realized, Denmark would need to import substantial amounts of wood to cover total national demand [13]. The long-distance transport of biomass (straw and wood), which has a very low energy density compared to fossil fuels, may lead to a less sustainable energy supply. It may also be beneficial to prioritize the scarce biomass energy resource for the production of high-grade fuels rather than low-grade thermal energy [13,14]. From a socio-economic perspective, using wind and heat pumps for electricity and heat production in regions such as Scandinavia and northern Germany is often a less expensive solution than biomass [15], and the potential for large-scale utility heat pumps already exists [16–18]. Biomass use can also be reduced in the heating sector by switching to sources such as solar thermal, industrial surplus heat and geothermal heat [19]. In their review of renewable energy system solutions, including electrolysis, heat pumps and sectoral integration, Mathiesen et al. [14] underline the importance of analyzing a wide range of available technologies to facilitate smart energy systems.

The objective of our study is to investigate how Sønderborg can become a low-$CO_2$ emitting municipality by 2029 in an energy efficient and cost-effective way, while also keeping its biomass consumption close to the limits of the locally available residual biomass resources. This goal is similar to what bioenergy villages in Germany and Austria have been trying to achieve; namely supplying the energy demand of the village solely with regional biomass sources, taking into account the local use of the agricultural and forest area [20]. For this purpose, we investigate the consequences of implementing novel energy conversion technologies such as large-scale heat pumps, biogas production, thermal gasification, electrolysis, biogas methanation and transport fuel synthesis. The modelling was performed using *Sifre*, a mixed-integer linear optimization tool, which optimizes energy flows and energy prices in all sectors of the specified energy system in discrete time steps. The *Sifre* tool is further described in Section 3.1. The results for the five different model scenarios for 2029 were evaluated and compared based on the following four indicators: the total system socio-economic costs, the energy system's net $CO_2$ emissions, the total biomass consumption (relative to the locally available resources) and the total energy conversion efficiency of the system.

The novelty of our work lies in modelling energy system scenarios containing a large number of different energy conversion technologies on an urban scale, including technologies not commonly employed today, such as electrolysis, fuel cells, thermal gasification and biofuel production. While a large body of literature exists on electrolysis and fuel cells as devices, there is very little discussion about them in a broader perspective of techno-economic energy system scenario analyses [21]. However, in this study we show that these technologies can contribute to future sustainable cities, the results encouraging municipalities not to overlook less common technologies. This work also focuses on the highly relevant issue of the scarcity of biomass resources. We include the comparison of planned biomass consumption with locally available residual biomass resources as one of the indicators used for comparing the outcomes of the scenarios, pointing out any scenarios where biomass imports would be necessary. Moreover, this work highlights the lack of sufficient investigations into whether the strategic plan actually represents the most feasible pathway for reaching the set goals. By expanding the scope of the investigated technologies and scenarios, it may be possible to identify alternative plans that perform better than the official plans in terms of socio-economy, energy efficiency and $CO_2$ emissions.

In Section 2, we review the literature concerning similar energy system studies and technologies used in the scenarios. In Section 3, the methodology used in this paper is described, including the model, scenarios, indicators and input data. In Section 4, we present the results of the case study. The results are discussed in Section 5, and the main conclusions are summarized in Section 6.

# 2 Literature review

The current Danish government has changed the previous targets of achieving $CO_2$-free electricity and heat supply by 2035 and transport by 2050. Besides the target of reaching 30% renewables in final energy consumption by 2020 (according to the EU's climate and energy package from 2008) [22], the policy of the current government is to reduce greenhouse gas (GHG) emissions by 2020 by 20% compared to 2005 in sectors outside the ETS quota scheme (transport, agriculture and individual heating). Denmark is close to achieving these goals already [23]. The targets for 2030 are yet to be stated, but are expected to follow the EU goal of 30% GHG reductions by 2030 in non-quota sectors. The long-term target for 2050 is to become independent of fossil fuels, understood as producing enough renewable energy to supply total Danish energy consumption on an average annual basis [24].

Since nations and cities show different levels of climate ambition, ensuring the consistency of local and national strategies for $CO_2$ reduction remains a challenge [25]. Thellufsen and Lund [26] address this challenge for the case of Sønderborg municipality by comparing its municipal energy plan [11] to a national scenario with the maximum total biomass consumption set at 67 TWh. While in that case the biomass consumption extrapolated from the local to national level is sufficient, in this paper we have considered the amount of biomass calculated as dry matter, presented in Section 4.4.

As mentioned in Section 1 and 3, among the technologies of interest in this paper is a reversible solid oxide fuel cell, which can operate either in an electrolysis (power-to-gas) or fuel cell (gas-to-power) mode. Hydrogen from electrolysis can be further used for upgrading biogas (see also Section 3.2.2). Graves et al. [27] demonstrate that a solid oxide cell operated in a reversible mode is more stable and not as prone to microstructural degradation as a solid oxide cell operated in constant electrolysis mode, suggesting its flexibility and usefulness in balancing the electrical load. Götz et al. [28] compare several electrolysis technologies and their conversion pathways, focusing on power-to-methane, that is, water electrolysis followed by hydrogen conversion to methane. A recent review of power-to-gas pilot plants shows that the technology is promising, but still has to overcome its high costs and insufficient efficiency [29]. Jentsch et al. [30] demonstrate that power-to-gas technologies are useful elements of an optimized 85% renewable energy system in Germany. Qadrdan et al. [31] show that electrolysis and a subsequent hydrogen injection into the gas grid can reduce wind curtailment and provide operational cost savings for connected electricity and gas systems. The characteristics and assessment factors for various types of fuel cells are reviewed by Sharaf and Orhan [32]. Stambouli and Traversa [33] evaluate solid oxide fuel cells in particular. Dodds et al. [34] discuss the underappreciated possibilities of using fuel cells in the heating sector, and their applications for power generation are examined by Choudhury et al. [35].

Traditionally, energy technologies have been analyzed either on a national or plant/single project level, but together with the increasing role of city-scale climate action, the local focus has been appearing more frequently in the latest energy planning literature. Urban energy methodologies, model types and future research trends are extensively reviewed and critically discussed by [36] and [37], and a detailed literature review of this topic is out of scope of this article.

The geographical focus of literature dealing with local energy analyses is quite broad: Østergaard and Lund [38] and Sperling and Möller [39] analyze energy scenarios for the Danish municipality of Frederikshavn (of similar size to Sønderborg). Other examples of city scale analysis include energy scenarios for a Hungarian town [40], implementing heat pumps in the Danish municipality of Aalborg [41], energy policy modelling using MarkAL-TIMES [42], the future energy mix for Bologna, Italy [43], urban planning and optimal energy mix for a Chinese eco-city [44], analyzing low-carbon scenarios for Beijing, China, using the LEAP model [45], and using a multi-objective optimization model and time series analysis for energy planning for a town in Brazil [46]. Orehounig et al. [47] describe a method for integrating the energy hub concept at a neighborhood level within a Swiss village, which has a target of becoming fossil-fuel free, and evaluate the resulting energy scenarios on the basis of their penetration of renewable energy and savings of $CO_2$ emissions [48]. The prerequisites and consequences of energy autarky, i.e. no imports of energy resources are modelled for a rural region in Austria [49]. While different technologies are discussed in these studies, none of them deals with modelling both biomass conversion and reversible electrolysis in a municipality, hence the focus of this paper.

# 3 Methodology

## 3.1 The *Sifre* tool

*Sifre* is a techno-economic energy system modelling tool, developed by the Danish electricity and gas transmission system operator Energinet.dk [50]. *Sifre* is a mixed-integer linear optimization program, which represents energy flows and energy prices in all sectors of the specified energy system in discrete time steps. A detailed description of the tool and its validation has been published by Energinet.dk [50]. No peer-reviewed work has been yet published based on the results of the *Sifre* tool, though [51] has conducted analyses using data extracted from *Sifre* optimization runs.

The objective of the *Sifre* optimization program is to minimize the total operating expenses of the specified energy system over a period, while fulfilling the specified energy demand during all time steps in the same period. In all optimization runs performed for this work, the calculation period was one year with a time resolution of one hour, resulting in 8760 discrete time steps. The *Sifre* tool relies on the external optimization solver *Gurobi* [52] for solving the optimization problem. Original routines for post-processing and analyzing all *Sifre* model outputs of this work were implemented using the programming languages *Matlab* and *Python.*

Capital expenses are not yet included in the current version of *Sifre*, but they will be incorporated in future model developments. The annualized capital expenses for all new investments (performed after 2014) in energy conversion and storage capacity have been accounted for in this work by adding them to the results post-optimization, based on the installed capacities in each scenario (see Section 3.3.1). Investments performed in 2014 or earlier were assumed to be sunk costs and were not included in the calculation. The scrap value of existing investments was also set to zero. The specific capital costs assumed for each technology are shown in Table A. 1 in Appendix A.

## 3.2 The model of Sønderborg municipality's energy system

Models of Sønderborg municipality's energy system for the years 2014 and 2029 were implemented in *Sifre*. 2029 was chosen because of the municipality's official goal of becoming $CO_2$ neutral by that year. Five scenarios for 2029, described in detail in Section 3.3, were investigated. Sections 3.2.2 to 3.2.7 describe all energy conversion pathways that are included in the 2029 scenarios. The structure of Sønderborg's energy system in 2014 was modelled and analyzed in order to compare the results of this modelling scenario with historical data and thereby calibrate the model. A schematic layout of the model for 2029 is shown in Figure 2.

### 3.2.1 Solid oxide electrolysis and fuel cells

The electrolyzers and fuel cells in the model are solid oxide cells (SOEC), because their expected efficiency and costs are projected to be superior to those of alkaline electrolyzers [53–56]. Electrolysis takes place at 650-800°C. A reverse process is conducted using a solid oxide fuel cell (SOFC), producing electricity, water and heat. It is assumed that the electrolyzer and the fuel cell form a reversible solid oxide cell that can alternate between operating in SOEC and SOFC mode [54]. The energy inputs, outputs and efficiency assumed for the electrolysis and fuel cell processes are listed in Table A. 2 in the Appendix. No electrolysis or fuel cell capacity is included in the 2014 scenario. The hydrogen produced in the model is utilized as an input for the fuel cells and for upgrading biogas to synthetic natural gas (SNG) and reforming of syngas to methanol, allowing for a more efficient utilization of the energy obtained from the scarce residual biomass resources [13]. Hydrogen is not used as an end-user fuel in the model, since, following the municipal strategic energy plan, the transport fuel mix is kept the same as now.

### 3.2.2 Biogas production and upgrade

In the model, biogas can be produced using manure, straw and electricity. We assume a wet matter mass input composition of 81% mixed animal manure and 19% straw [57]. The energy inputs, outputs and the efficiency of the biogas production and upgrading processes are listed in Table A. 2. In the model, biogas can either be used directly in gas boilers or be upgraded to natural gas quality. The biogas is upgraded through either a conventional $CO_2$ removal process or a more energy-efficient methanation [13]. The upgraded biogas is injected into the local gas distribution network in Sønderborg municipality. No biogas production or upgrade capacity is included in the 2014 scenario.

### 3.2.3 Syngas production and reformation to methanol

The model includes the thermal gasification of solid biomass and waste for the production of synthesis gas (syngas), which is reformed to methanol for use as a transport fuel, partly replacing the diesel and gasoline demand in Sønderborg municipality. In principle, methanol could be reformed further to dimethyl ether (DME), but this process is disregarded in this paper, since it is argued that methanol may be more suitable as an electrofuel than DME [21,58]. The energy inputs, output and efficiencies of the gasification and reformation processes are listed in Table A. 2. No syngas production or reformation capacity is included in the 2014 scenario.

### 3.2.4 Individual heating supply

Approximately 428 GWh, corresponding to 53% of the final heat demand in Sønderborg municipality, was supplied by individual heating in 2014 [11]. Five types of individual heating supply are considered in the model; their energy inputs and efficiencies are listed in Table A. 3. In the model, individual heat pumps are assumed to operate with a coefficient of performance (COP) equal to 3.0, in line with recommendations from [59].

### 3.2.5 District heating supply

The district heating system of Sønderborg municipality is composed of five separate district heating networks, which in the model are represented as one fully interconnected network. Approximately 383 GWh, corresponding to 47% of the end-user heat demand in the municipality, was supplied in the form of district heating in 2014 [11]. To satisfy this demand and accommodate the 24% network transmission losses, 504 GWh of heat were generated. The energy inputs, outputs and efficiencies of all district heating production units were obtained from the Danish Energy Agency [60].

The assumed energy inputs, outputs and efficiencies of all heat production units are listed in Table A.4. The largest combined heat and power (CHP) plant in the municipality is located in the city of Sønderborg and consists of two units: a waste incineration unit and a gas turbine unit. The remaining

CHP plants are smaller gas turbine units. In addition, several boilers running on natural gas, biomass and electricity exist in the municipality. No biogas boilers were present in the municipality's energy system in 2014, but they are included in some of the 2029 scenarios.

The utility-scale heat pumps are assumed to operate with a coefficient of performance (COP) equal to 3 [61]. Production of the solar heating plants in the model was defined using an hourly time series based on the historical production of an existing solar heating facility in Sønderborg municipality in 2014 [62]. One of the district heating production plants in Sønderborg municipality is a geothermal plant, which is connected to an absorption heat pump and a biomass boiler. Based on [60] it is assumed that the 38% of energy inputs come from the geothermal unit and 62% from the biomass unit.

### 3.2.6 Electricity production and import/export

In 2014, only 16.3% of Sønderborg's total electricity consumption was generated within the municipal borders, using an incineration CHP plant, natural gas CHP plants, onshore wind turbines and photovoltaics [11]. The municipality is connected to the Western-Danish electricity grid with an effective transmission capacity of 270 MW [11]. In the model, no constraints in electricity flow within the distribution network of Sønderborg municipality are assumed.

The installed renewable electricity generation capacity in Sønderborg municipality in 2014 was 14.6 MW onshore wind turbines and 1.48 MW photovoltaics [63]. For the 2014 scenario, we used historical time series for wind and photovoltaic production in southern Denmark. For the 2029 scenarios, time series for wind and photovoltaic generation were provided by Energinet.dk [64].

### 3.2.7 Fossil fuel and natural gas import

All natural gas, gasoline, diesel and heating oil is imported in 2014 [11]. Sønderborg municipality is connected to the national gas transmission grid [11]. Natural gas is used in CHP plants and boilers and for industrial processes. In the 2029 scenarios, transport is partly based on natural gas. Diesel and gasoline are consumed by the transport sector and heating oil is only used for individual heating.

## 3.3 Scenario definitions

### 3.3.1 Scenario descriptions and installed energy capacities

The modelled scenarios are described in Table 1. The calibration scenario, labelled 0, represents the year 2014 and is based on historical data [11,60,63]. The five remaining scenarios A-E represent alternative options for the state of Sønderborg municipality's energy system in 2029. Scenario A seeks to emulate the strategic energy plan of Sønderborg municipality [11]. Scenario B represents a "Biomass" scenario in which fossil fuel-consuming plants have mostly been replaced by units that combust biomass. Scenario C represents an "Electrification" scenario in which fossil fuels have mostly been replaced by electricity-consuming units, such as heat pumps. Scenario D ("Electrolysis") is an extension of scenario C, with the addition of hydrogen production from electrolysis and syngas production from biomass gasification. Scenario E ("Reversible electrolysis") is an extension of scenario D, with the assumption that the electrolyzers are also able to operate in fuel cell mode. Another difference is that natural gas boilers are only used in scenarios 0 and A, but are replaced by biogas boilers in scenarios B, C and D. Gas boilers are not used in scenario E. Please note that scenario A can be viewed as a compromise between scenarios B and C.

**Table 1.** Modelled scenarios and their descriptions.

| Year | Scenario symbol | Scenario name | Description |
|---|---|---|---|
| 2014 | 0 | Model calibration | Sønderborg's energy system in 2014 - a comparison with historical data. |
| 2029 | A | Municipal plan | Future scenario according to the current strategic energy plan of Sønderborg municipality [11,65]. |
| 2029 | B | Biomass | Future low fossil-fuel scenario where biomass replaces fossil fuels, without any significant electrification (e.g. no utility-scale heat pumps). |
| 2029 | C | Electrification | Future low fossil-fuel scenario with a focus on electrification, where biomass consumption is kept close to the locally available limits. |
| 2029 | D | Electrolysis | Same as the Electrification scenario, with the addition of gasification and solid oxide electrolysis for a more energy-efficient biomass utilization. All biogas upgrade is conducted through biogas methanation instead of $CO_2$ removal. |
| 2029 | E | Reversible electrolysis | Same as the Electrolysis scenario, with the addition of reversible solid oxide cells for electrolysis and fuel cell operation. |

The installed capacities for each conversion unit across all scenarios can be seen in Table 2. The capacities in scenarios B-E were chosen by the authors using scenario A and the general scenario descriptions above as guidelines.

**Table 2.** Total installed capacities for each type of conversion unit in the model, for all scenarios.

| Conversion unit | Product | Installed capacity (MW) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0 | A | B | C | D | E |
| Natural gas boilers | District heating | 160.1 | 50.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Biogas boilers | District heating | 0.0 | 0.0 | 50.0 | 10.0 | 10.0 | 10.0 |
| CHP (natural gas) | District heating<br>Electricity | 64.8<br>71.4 | 64.8<br>71.4 | 0.0<br>0.0 | 0.0<br>0.0 | 0.0<br>0.0 | 0.0<br>0.0 |
| CHP (waste) | District heating<br>Electricity | 20.0<br>4.5 | 20.0<br>4.5 | 20.0<br>4.5 | 20.0<br>4.5 | 20.0<br>4.5 | 20.0<br>4.5 |
| Geothermal + absorption heat pump | District heating | 43.0 | 43.0 | 43.0 | 10.0 | 0.0 | 0.0 |
| Biomass boilers | District heating | 17.4 | 25.6 | 140.4 | 25.6 | 25.6 | 25.6 |
| Electric boilers | District heating | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 |
| Heat pump (utility-scale) | District heating | 0.0 | 50.0 | 0.0 | 187.8 | 195.3 | 203.4 |
| Solar heating | District heating | 26.1 | 194.9 | 194.9 | 194.9 | 194.9 | 194.9 |
| Biomass boilers | Individual heating | 17.1 | 11.4 | 57.4 | 11.4 | 0.0 | 0.0 |
| Electric heating | Individual heating | 25.7 | 17.1 | 17.1 | 17.1 | 17.1 | 17.1 |
| Natural gas heaters | Individual heating | 57.1 | 21.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| Oil heaters | Individual heating | 32.8 | 19.4 | 0.0 | 0.0 | 0.0 | 0.0 |
| Heat pumps | Individual heating | 6.0 | 11.4 | 6.0 | 52.0 | 63.4 | 63.4 |
| Photovoltaics | Electricity | 14.8 | 40.0 | 40.0 | 40.0 | 40.0 | 40.0 |
| Wind turbines (onshore) | Electricity | 14.6 | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 |
| Wind turbines (coastal-near) | Electricity | 0.0 | 120.0 | 100.0 | 140.0 | 150.0 | 150.0 |
| Solid oxide electrolyzer cells (SOEC) | Hydrogen<br>District heating | 0.0<br>0.0 | 0.0<br>0.0 | 0.0<br>0.0 | 0.0<br>0.0 | 20.0<br>0.4 | 40.0<br>0.8 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Solid oxide fuel cells (SOFC) | Electricity<br>District heating | 0.0<br>0.0 | 0.0<br>0.0 | 0.0<br>0.0 | 0.0<br>0.0 | 0.0<br>0.0 | 10.0<br>1.5 |
| Anaerobic digestion | Biogas | 0.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 |
| Biogas $CO_2$ removal | Natural gas | 0.0 | 10.0 | 10.0 | 10.0 | 0.0 | 0.0 |
| Biogas methanation | Natural gas | 0.0 | 0.0 | 0.0 | 0.0 | 16.0 | 16.0 |
| Gasifiers | Syngas | 0.0 | 0.0 | 0.0 | 0.0 | 12.0 | 12.0 |
| Syngas reformation | Methanol | 0.0 | 0.0 | 0.0 | 0.0 | 10.0 | 10.0 |

The installed capacities for solar heating, photovoltaics and onshore wind turbines equal those assumed in Sønderborg's strategic energy plan. Due to land-use considerations, we have assumed that further expansion of this production capacity is impossible, and the installed solar heating, photovoltaics and onshore wind capacity therefore remain constant throughout scenarios A-E. An expansion of coastal-near wind turbines beyond the strategic energy plan is assumed in scenarios C-E to partially compensate for the increased total electricity demand in these scenarios.

The pathway of biogas production and upgrade to natural gas quality through $CO_2$ removal is introduced in scenarios A-C. In scenarios D and E, all biogas upgrade is assumed to take place by biogas methanation. The pathway of syngas production, along with reformation to methanol, is only present in scenarios D and E. Hydrogen production is thus only needed in scenarios D and E, and no SOEC production capacity is applied in any of the other scenarios. Finally, the option of operating the solid oxide cells in fuel cell mode is only present in scenario E.

Figure 2 shows the model structure for Sønderborg's energy system in 2029, depicting the energy sources, conversion units, transmission and distribution networks and energy services and their interconnections. The energy flows within each distribution network are not constrained in the model.

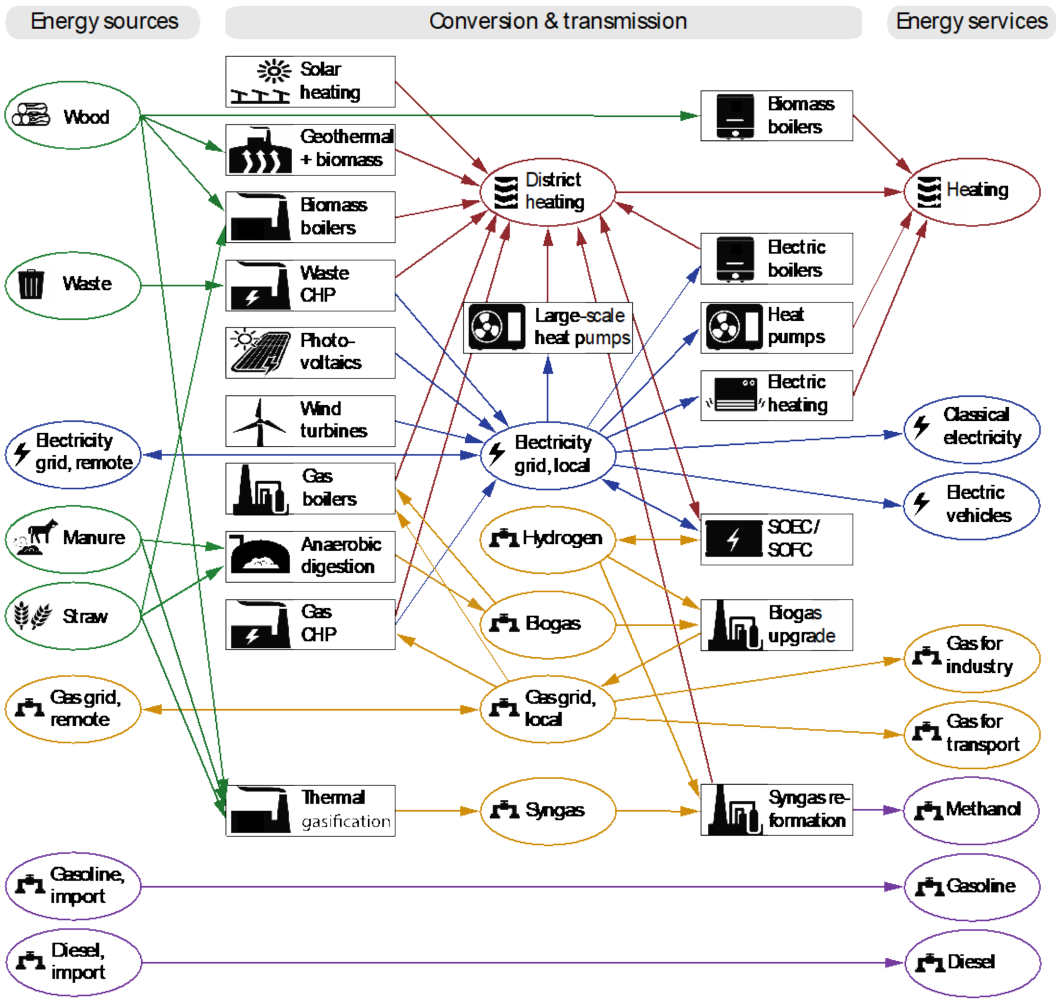


**Figure 2.** A schematic representation of the model of Sønderborg municipality's energy system showing the components and energy flows of the model for the 2029 scenarios. Energy sources and imports to the municipality's energy system are shown on the left of the flow chart and energy services (demand) in the municipality are shown on the right. Rectangular fields denote energy conversion units and elliptical fields denote energy carriers and distribution networks. Biomass is indicated in green, electricity in blue, natural gas in orange and petroleum products in violet. For simplification, the schematic excludes energy storage facilities.

### 3.3.2 Locally available residual biomass resources

The locally available residual biomass resources in Sønderborg municipality are listed in Table A. 5 in Appendix A. In scenarios 0 and A, the biomass consumption was not restricted. In scenarios C-E, the available biomass in the model was restricted based on availability for 2029. In 2014, the waste consisted of both local and imported municipal waste, and it is assumed in all 2029 scenarios that the import of waste can be regulated to match the demand. Table 10 in Section 4.4 shows a comparison of locally used biomass in each 2029 scenario and corresponding national amount of biomass.

### 3.3.3 Demand for energy services

Demand for energy services in the 2014 model scenario was based on historical data [11,60,63]. In scenario A it was based on Sønderborg's strategic energy plan [11], in scenarios B-E it was decided upon by the authors as an aspect of developing the scenarios, using scenario A and the general scenario descriptions from Section 3.3.1 as guidelines. Table 3 shows the assumed energy demand for each energy service type across all scenarios. The model optimizes operation against the demand for these energy services on an hourly basis according to the hourly demand distribution for each type.

**Table 3.** The annual demand for each type of energy service in the model.

| Energy service | Demand in each scenario (GWh/year) | | | | | |
|---|---|---|---|---|---|---|
| | 0 | A | B | C | D | E |
| District heating | 383 | 445 | 445 | 445 | 445 | 445 |
| Individual biomass heating | 39 | 26 | 187 | 26 | 0.0 | 0.0 |
| Individual gas heating | 199 | 74 | 0.0 | 0.0 | 0.0 | 0.0 |
| Individual oil heating | 116 | 68 | 0.0 | 0.0 | 0.0 | 0.0 |
| Individual electric heating | 53 | 41 | 41 | 41 | 41 | 41 |
| Individual heat pumps (heat prod.) | 21 | 40 | 21 | 182 | 208 | 208 |
| Electricity (classical) | 440 | 305 | 305 | 305 | 305 | 305 |
| Electricity (transport) | 0.1 | 19 | 19 | 34 | 34 | 34 |
| Natural gas (industry) | 279 | 279 | 279 | 279 | 279 | 279 |
| Natural gas (transport) | 0.0 | 30 | 30 | 0.0 | 0.0 | 0.0 |
| Gasoline (transport) | 230 | 155 | 155 | 155 | 115 | 115 |
| Diesel (transport) | 270 | 300 | 300 | 300 | 260 | 260 |
| Methanol (transport) | 0.0 | 0.0 | 0.0 | 0.0 | 80 | 80 |
| **Total energy demand** | **2030.1** | **1782** | **1782** | **1767** | **1767** | **1767** |

District heating demand is higher in 2029 than in 2014 due to an anticipated conversion of some areas from individual heating to district heating, in line with the strategic energy plan. It remains constant in scenarios A-E. Consumption of individual gas and oil heating is significantly reduced in scenario A compared to 2014. In scenarios B-E gas and oil are not used for individual heating. Individual heating is primarily supplied by biomass boilers in scenario B and by heat pumps in scenarios C-E. Time series for the district heating demand profile were based on measured data for 53 single-family houses in Sønderborg, obtained from the municipality's district heating company [66]. The same heat demand profile was also assumed for individual heating.

Classical electricity demand, which includes all electricity demand except heat pumps, electric vehicles and electrolysis, is lower in 2029 than in 2014 and identical in scenarios A-E, as anticipated in the strategic energy plan. In scenarios A and B, the electricity demand of electric vehicles follows the projection from Sønderborg's strategic energy plan. Electricity demand for heat pumps is not a direct input parameter in the model; it is dictated by the end-user heat demand from individual and large-scale heat pumps. Time series for Danish classical and electric vehicle electricity demand were obtained from Energinet.dk [64]. Classical electricity demand time series for 2014 were based on measured data while time series for 2029 were based on simulations by Energinet.dk. Demand response has been excluded from this study.

The value and profile for industrial gas demand were obtained from Energinet.dk [64]. The industry gas consumption remains unchanged from 2014 to 2029. Some natural gas for transport is consumed in in scenarios A and B. The increase in electric vehicle energy demand in scenarios C-E compared to scenarios A and B comes from the assumption that the vehicles running on natural gas in scenarios A and B, switch to electricity in scenarios C-E, with a double efficiency compared to gas.

We assume that total demand for liquid transport fuels will decrease from 2014 to 2029, due to the increased energy efficiency of the vehicles. Total liquid transport fuel is the same in scenarios A-E. In scenarios D and E, methanol replaces some of the gasoline and diesel.

### 3.3.4 $CO_2$ emissions

The $CO_2$ emission factors recommended by the Danish Energy Agency [67] were used for calculating the total $CO_2$ emissions arising from fuel consumption for each scenario. The $CO_2$ emissions of electricity imports and exports from the Western Danish electricity grid are accounted for in the total $CO_2$ emissions value by adding or subtracting the corresponding amount of average $CO_2$ emissions in the Danish electricity generation mix: 270 kg/MWh in 2014 and 100 kg/MWh in 2029, in line with data and forecast from the Danish Energy Agency. Any indirect $CO_2$ emissions, such as those arising from the construction and scrapping of power plants, are excluded from the model, as such life-cycle analysis is outside the scope of this work.

Although $CO_2$ is not the only gas species responsible for the greenhouse effect, other greenhouse gases including water vapor, methane, nitrous oxide and ozone are excluded from the model. Furthermore, biomass, gasoline and diesel combustion releases NOx, but its quantification is beyond the scope of this paper. As $CO_2$ emissions are the largest contributor to the greenhouse effect globally, they have been selected as an environmental indicator in this work to enable direct comparison with existing data and climate targets for Sønderborg and with other energy planning literature that uses $CO_2$ emissions as an indicator.

### 3.3.5 Electricity, fuel and $CO_2$ quota prices

The electricity prices, fuel prices and $CO_2$ quota prices used in the model are shown in Table A. 6 in Appendix A. The electricity price time series for 2014 is the historical electricity Nord Pool spot price in Western Denmark. The time series used for the 2029 scenarios come from Energinet.dk's scenario simulations [64]. The 2029 price time series match the wind and photovoltaic generation time series described in Section 3.2.6, as they originate from the same simulation. The prices of fossil fuels were inserted in the form of hourly time series in 2014 and as a constant (average) projected value in 2029.

## 3.4 Assessment indicators

This study aims to investigate how Sønderborg can become a low-$CO_2$ emitting municipality in 2029 in an energy-efficient and cost-effective way, given the limited locally available residual biomass resources. The scenario results were compared using four indicators described in Table 4. The total system socio-economic cost is the sum of the fuel cost, operation and maintenance (O&M) costs, the annualized investment costs for investments performed after 2014 and the $CO_2$ emission quota costs. Taxes and subsidies are excluded. The calculation of total net $CO_2$ emissions is described in Section 3.3.4. The total biomass consumption is the sum of the energy inputs from wood, straw, manure and waste in the model. The total system energy efficiency is the ratio of the total end-user energy outputs to the total primary energy inputs in the system.

These indicators were selected in order to assess the feasibility of the scenarios in terms of economy (total system socio-economic costs), energy efficiency (total system energy conversion efficiency), greenhouse effect impact (total $CO_2$ emissions) and sustainability (total biomass consumption relative to the locally available residual biomass resources). Since different indicators may be valued differently depending on a decision-making perspective, rather than determining and presenting performance values for the scenarios by means of an arbitrary choice of weighting factors, we have chosen to present and compare the results in terms of four indicators, thereby treating all indicators as equally important.

The most feasible scenario is the one that best combines the lowest total socio-economic costs, the lowest total $CO_2$ emissions, a total biomass consumption close to or under the locally available residual biomass resources and the highest total energy system efficiency. Please note that the scenario results, expressed via the indicators, only reflect a comparison of the investigated scenarios and that we make no claim to have found a global optimum for the configuration of Sønderborg's energy system in 2029. The results are thus intended as guidelines for energy policy and energy system planning on a medium-sized northern European urban scale, and not as a manual for the exact configuration of such a system.

**Table 4.** Indicators used for comparing the results of scenarios A-E. All values are compared on an annual basis.

| Indicator | Unit | Description |
|---|---|---|
| Total energy system socio-economic cost | €/year | The sum of the fuel cost, O&M costs, the annualized investment costs and the $CO_2$ emission costs. |
| Total system $CO_2$ emissions | ton $CO_2$/year | Net $CO_2$ emissions arising from Sønderborg municipality's energy consumption. |
| Total biomass consumption | % | Relative to the total of locally available residual biomass resources. |
| Total system energy conversion efficiency | % | The ratio of the total energy outputs to the total energy inputs in the energy system. |

# 4 Results

## 4.1 Model calibration

A comparison between the results of scenario 0 and historical data for 2014 is shown in Table 5 for the main types of energy flows. A more detailed comparison of the model results with 2014 statistics on fuel consumption for district heating and individual heating can be seen in Tables A.7 and A.8 in Appendix A.

**Table 5.** A comparison of the end-use energy consumption between the model calibration scenario and statistics from 2014.

| **Energy type** | **Energy consumption (GWh/year)** | | | |
|---|---|---|---|---|
| | **Scenario 0** | **Historical data** | **Deviation** | **Data reference** |
| District heating | 383.3 | 383.0 | 0.0% | [68] |
| Electricity (classical) | 440.0 | 441.0 | 0.0% | [68] |
| Natural gas (non-district heating) | 474.3 | 477.4 | -0.6% | [63] |
| Biomass (non-district heating) | 43.3 | 48.2 | -10.2% | [63] |
| Oil, gasoline & diesel | 606.9 | 622.8 | -2.6% | [63] |
| Coal and coke | 0.0 | 13.6 | -100% | [63] |
| **Total** | **1947.8** | **1986.2** | **1.9%** | |

As shown in Table 5 (as well as Tables A.7 and A.8), the results of scenario 0 agree with historical data from 2014. The deviation between the model and the statistics regarding biomass consumption is partly due to the consumption of bio-oil for individual heating, which has not been included in the model. Coal and coke consumption has also been excluded from the model, as this only concerns brick factories and its inclusion would have increased the $CO_2$ emissions in scenario 0 by an estimated 5 kton/year, corresponding to 1%. The total energy consumption in the model and the statistics deviate by only 1.9%, making the model well calibrated for the present case and suitable for future analyses of the system.

## 4.2 Energy flows in the 2029 scenarios

Figure 3 shows a Sankey diagram of all the energy flows in scenario A. Corresponding Sankey diagrams for scenarios B-E are shown in Figures A.1-A.4 in Appendix A. Table 6 shows annual fuel consumption and electricity imports and exports for all scenarios. Table 7 shows the annual energy outputs of all energy conversion units in the model across all scenarios. A detailed comparison of the scenarios based on the indicators is conducted in Section 4.3.

As shown on the right of the diagram, about 33% of final energy consumption in Sønderborg municipality in 2029 is planned to consist of heat, of which 64% will be supplied by district heating. The share of heating in final energy consumption is substantially lower than in the calibration scenario due to anticipated improvements in building insulation and energy efficiency of the heat generation units. In all 2029 scenarios, Sønderborg has transitioned from importing most of its electricity demand to being a large electricity exporter. In scenario A, 49% of all electricity generated in Sønderborg is exported beyond the municipal borders. A significant portion of the electricity generation comes from the coastal-near wind turbines that play a central role in Sønderborg's strategic energy plan. While the total amount of biomass consumption in scenario A is smaller than in scenario 0, new conversion pathways such as anaerobic digestion and biogas upgrade are planned. In scenario A, natural gas imports are reduced by 34% compared to 2014. However, fuel imports for transport remain at the same level as in scenario 0.

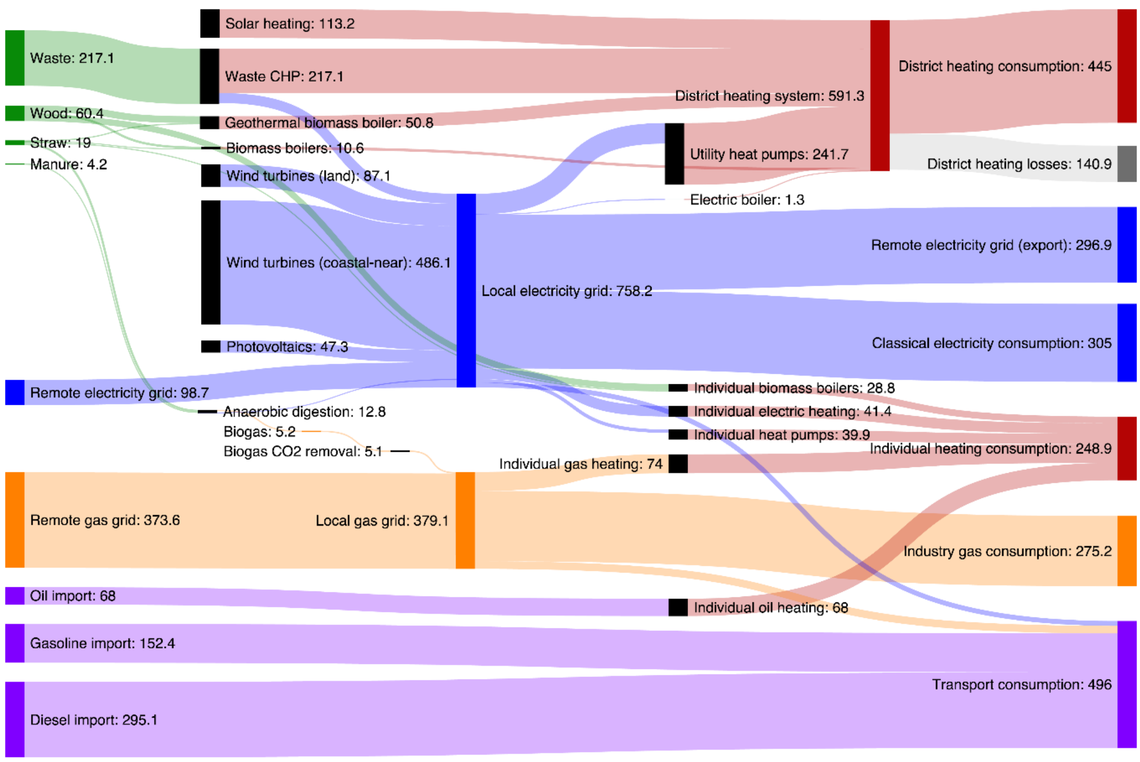

**Figure 3.** A Sankey diagram of the model results of scenario A. The numbers denote the total energy outflow from each node. All numbers in GWh/year.

As Table 6 shows, the main difference in the resulting fuel consumption among scenarios A-E concerns solid biomass: waste, wood and straw. For waste, it is highest in scenario A and decreases by 10% in scenario B, by 69% in scenario C and by 51% in scenarios D and E. The highest consumption of wood occurs in scenario B and is lower by 85% in scenario A, by 94% in scenario C and by 90% in scenarios D and E. Straw consumption is also the highest in scenario B and decreases by 76% in scenario A, by 94% in scenario C and by 68% in scenarios D and E.

**Table 6.** The resulting fuel consumption and electricity imports and exports across all scenarios.

| Type | Fuel consumption and electricity import/export (GWh/year) | | | | | |
|---|---|---|---|---|---|---|
| | 0 | A | B | C | D | E |
| Waste | 218.0 | 217.1 | 194.6 | 67.2 | 106.5 | 105.7 |
| Wood | 164.7 | 60.4 | 393.2 | 24.4 | 40.4 | 40.4 |
| Straw | 32.0 | 19.0 | 79.1 | 4.4 | 25.4 | 25.7 |
| Manure | 0.0 | 4.2 | 4.2 | 0.0 | 2.6 | 2.7 |
| Electricity imports | 423.5 | 98.7 | 78.8 | 134.1 | 134.2 | 134.7 |
| Electricity exports | 0.0 | 296.9 | 279.0 | 265.2 | 281.6 | 268.6 |
| Natural gas imports | 565.6 | 373.6 | 299.5 | 275.2 | 270.3 | 270.1 |
| Oil imports | 115.0 | 68.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Gasoline imports | 226.2 | 152.4 | 152.4 | 152.4 | 113.1 | 113.1 |
| Diesel imports | 265.6 | 295.1 | 295.1 | 295.1 | 255.7 | 255.7 |

As seen is Table 7, the main difference in the resulting outputs among scenarios A-E concerns wind energy and district heating production. The output of coastal wind turbines is the greatest in scenarios D and E and drops by 20% in scenario A, by 33% in scenario B and by 7% in scenario C. The electricity and heat output of the waste CHP is the largest in scenario A and lower by 10% in scenario B, by 69% in scenario C and 70% in scenario D and E. The geothermal-biomass boiler and the biomass boiler produces heat only in scenarios A and B. Utility heat pumps produce the biggest output in scenario C, and it is lower by 43% in scenario A, and by 2% and 1% in scenarios D and E, respectively. Methanation, SOEC, SOFC, gasification and syngas reformation are only represented in scenarios D and E.

**Table 7.** The resulting outputs of all energy conversion units across all scenarios. The energy output for each type of individual heating is identical to the demand for the individual heating type, which is presented in Table 2 in Section 3.3.1.

| Conversion unit | Output type | Energy output (GWh/year) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0 | A | B | C | D | E |
| Wind turbines (land) | Electricity | 29.2 | 87.1 | 87.1 | 87.1 | 87.1 | 87.1 |
| Wind turbines (coastal-near) | Electricity | 0.0 | 486.1 | 405.1 | 567.1 | 607.6 | 607.6 |
| Photovoltaics | Electricity | 14.0 | 47.3 | 47.3 | 47.3 | 47.3 | 47.3 |
| Solar heating | District heating | 16.5 | 113.2 | 123.1 | 123.3 | 123.7 | 123.7 |
| Waste CHP | District heating | 173.7 | 173.7 | 155.7 | 53.8 | 52.9 | 52.3 |
| Waste CHP | Electricity | 39.2 | 39.1 | 35.0 | 12.1 | 11.9 | 11.8 |
| Geothermal biomass boiler | District heating | 170.7 | 50.8 | 144.0 | 0.0 | 0.0 | 0.0 |
| Biomass boiler | District heating | 46.8 | 10.6 | 166.1 | 0.0 | 0.0 | 0.0 |
| Gas boilers | District heating | 91.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Utility heat pumps | District heating | 0.0 | 241.7 | 0.0 | 424.3 | 414.5 | 421.6 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Electric boilers | District heating | 5.2 | 1.3 | 1.2 | 0.0 | 0.0 | 0.0 |
| Anaerobic digestion | Biogas | 0.0 | 5.2 | 5.2 | 0.0 | 3.1 | 3.3 |
| Biogas $CO_2$ removal | Natural gas | 0.0 | 5.1 | 5.1 | 0.0 | 0.0 | 0.0 |
| Biogas methanation | Natural gas | 0.0 | 0.0 | 0.0 | 0.0 | 5.2 | 5.5 |
| SOEC electrolysis | Hydrogen | 0.0 | 0.0 | 0.0 | 0.0 | 17.8 | 42.1 |
| SOFC fuel cells | Electricity, heat | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 20.5 |
| Gasification | Syngas | 0.0 | 0.0 | 0.0 | 0.0 | 81.3 | 81.3 |
| Syngas reformation | Methanol | 0.0 | 0.0 | 0.0 | 0.0 | 79.0 | 79.0 |

## 4.3 Indicators

In the following, the results of all scenarios are presented and compared in terms of the indicators introduced in Section 3.4. Figure 4 shows the annual energy inputs to the system by type and the annual end-use energy outputs by sector. The energy outputs are very similar in all 2029 scenarios, as the energy demands against which the model optimizes system's operation are very similar in all cases, as shown in Table 2. However, these demands are supplied using very different energy inputs in each of the scenarios A-C. The definitions of scenarios C-E differ more subtly and therefore their energy inputs are very similar.

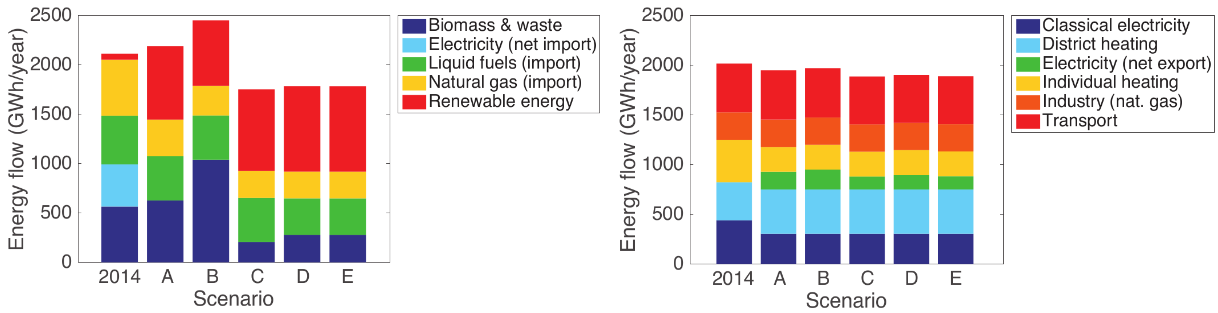


**Figure 4.** Total annual energy inputs by energy source (left) and total end-user energy outputs by sector (right).

Table 8 shows the results for the total energy efficiency indicator, defined as the ratio between annual total end-user energy outputs and annual total energy inputs. Most scenarios have a total energy efficiency greater than 1, because the heat pumps in the model yield 3.0 units of heat output for every unit of electricity input. It is clear that scenario B (biomass) has the lowest total energy efficiency, hardly surprising given that this scenario has lowest heat pump capacity out of the 2029 scenarios. Scenario A (the municipal plan) is slightly more energy efficient than the reference scenario. Scenarios C-E, which are those with a high degree of electrification (including heat pumps) and low biomass consumption, are clearly most efficient out of the investigated scenarios and require by far the least energy inputs to fulfill end-user energy demand. Scenarios D and E are slightly less energy efficient than scenario C due to conversion losses in technologies such as solid oxide cells and methanol production from the thermal gasification of biomass.

**Table 8.** Total annual energy inputs, total annual end-user energy outputs and total system energy efficiency (the ratio between total outputs and total inputs) for all scenarios.

| Scenario | Total energy inputs (GWh/year) | Total end-user energy outputs (GWh/year) | Total system energy efficiency |
|---|---|---|---|
| 0 (calibration) | 1961 | 2017 | 1.029 |
| A (municipal plan) | 1864 | 1947 | 1.045 |

| | | | |
|---|---|---|---|
| B (biomass) | 2081 | 1970 | 0.974 |
| C (electrification) | 1643 | 1887 | 1.149 |
| D (electrolysis) | 1680 | 1903 | 1.133 |
| E (reversible electrolysis) | 1679 | 1890 | 1.126 |

Figure 5 gives the annual socio-economic system costs for scenarios A-E. Scenarios D and E achieve the lowest costs (scenario E being less expensive by roughly 60,000 EUR), which is due to savings in fuel expenses and $CO_2$ emission costs. Moreover, the composition of the costs changes with increasing renewable energy share, electrification and energy efficiency, because the fuel costs become less important and the energy system becomes more capital cost intensive. As a result, scenario B has the lowest capital expenses and the highest fuel expenses, while the opposite is true for scenarios D and E.

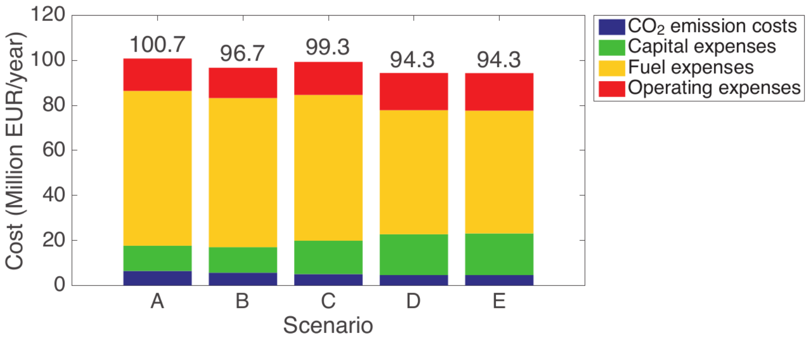


**Figure 5.** Total annual socio-economic system costs in scenarios A-E.

Total annual $CO_2$ emissions are shown in Figure 6. Emissions are substantially lower in 2029 than in 2014. This is due to large reductions in $CO_2$ emissions from the heating sector because of a change in the generation mix, and negative emissions from electricity generation in 2029 (as exports of low-$CO_2$ emitting electricity are assumed to offset Sønderborg's $CO_2$ emissions). In scenarios C-E, the $CO_2$ emissions from heat generation are eliminated. Transport and industry remain the main $CO_2$ emitters, as no large changes in fuel consumption are assumed in these sectors compared to the reference scenario. In scenarios D and E, some fossil fuel consumption by transport has been replaced by methanol produced from biomass. This leads to a slight decrease in $CO_2$ emissions from transport and makes these two scenarios the best ones in terms of minimizing total annual $CO_2$ emissions.

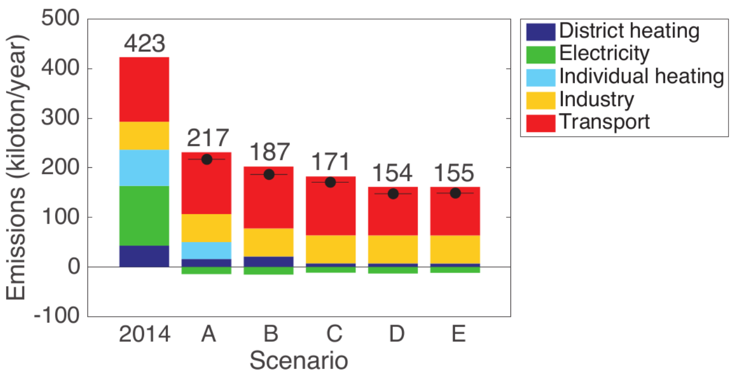


**Figure 6.** Annual $CO_2$ emissions by sector in each scenario. In scenarios A-E, the electricity sector in Sønderborg municipality has negative $CO_2$ emissions due to its net exports of electricity.

Table 9 shows total annual biomass consumption for each scenario as a percentage of the locally available residual biomass resources (shown in Table A.5 in Appendix A). In all scenarios, wood constitutes a dominant proportion of biomass consumption and wood consumption in none of the scenarios is strictly within the limits of locally available resources. The requirements regarding the local sustainability of biomass consumption are highly dependent on local and national policies. If the aim is to be completely self-sufficient in using biomass for energy purposes, scenario C is the best, even though it shows very low utilization of resources with better availability than wood: manure and straw. If, however, it is acceptable to supplement the locally available biomass resources with limited imports, then scenarios D and E perform very well, followed by A. These scenarios utilize manure and straw better than scenario C. The best utilization of manure and straw in total occurs in scenario B, though this scenario would require vast imports of wood, thereby decreasing its sustainability.

**Table 9.** Annual biomass consumption as a percentage of the annual local biomass resource of each type (measured in terms of energy content).

| Biomass type | 2014 | A | B | C | D | E |
|---|---|---|---|---|---|---|
| Manure | 0.0% | 8.1% | 5.7% | 0.03% | 3.5% | 3.7% |
| Straw | 36.5% | 8.1% | 25.0% | 1.4% | 8.0% | 8.1% |
| Wood | 1003% | 393.6% | 2070% | 128.5% | 212.8% | 212.8% |

To summarize, scenario C performs best in terms of total energy efficiency of the system, closely followed by scenarios D and E. Scenario C also performs best in terms of keeping biomass consumption within the locally available limits, again followed by D and E. Scenarios D and E perform best in terms of annual total system costs, followed by scenario B. Scenarios D and E perform best in terms of total annual $CO_2$ emissions, followed by scenario C. Scenarios C-E perform better than scenario A on all indicators.

## 4.4 Local versus national biomass consumption

Although the focus of this study is the municipality of Sønderborg, a question arises: if all Denmark was to use the same amount of biomass per capita, that each scenario requires, how great would Danish national biomass consumption for energy purposes be? Table 10 shows the amount of biomass used in each scenario and how it corresponds with the required national level.

**Table 10.** Comparison of locally used biomass in each scenario and corresponding national amount of biomass. As of 2016, Sønderborg municipality had 74,732 inhabitants [69] out of a total Danish population of 5,717,000 [70].

| Scenario | Unit | A | B | C | D | E |
|---|---|---|---|---|---|---|
| Locally used amount | GWh | 625 | 1000 | 200 | 250 | 250 |
| Per capita consumption | GWh/ inhabitant | 0.008 | 0.013 | 0.003 | 0.003 | 0.003 |
| Corresponding national amount | GWh | 47,813 | 76,500 | 15,300 | 19,125 | 19,125 |
| Corresponding national dry matter amount (assuming 17.5 GJ/t) | t | 9,835,817 | 15,737,143 | 3,147,429 | 3,934,286 | 3,934,286 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Corresponding national dry matter amount (assuming 9 GJ/t) | t | 19,125,200 | 30,600,000 | 6,120,000 | 7,650,000 | 7,650,000 |

Total future Danish biomass production potential was calculated at between 7.2 and 11.1 million tons of dry matter [71]. As Table 10 shows, depending on the assumptions regarding the types of biomass used and their energy content, the nation's biomass resource would suffice only in case of scenarios C-E and partly A (only if very high energy content of the biomass used is assumed). Substantial imports would be required to cover the high biomass demand in the case of scenarios A or B. Denmark is rather rich in residual biomass resources, with substantial amounts of residual biomass arising from agriculture and pig farming. If a country such as Denmark is predicted to be unable to meet its biomass demand for energy purposes without imports, therefore it is very likely that the same situation could arise in many other regions and countries that share the Danish municipalities' plans of transitioning to biomass combustion for heat and electricity generation. In the long run, such a development could lead to higher biomass prices and reduced security of supply.

## 4.5 Heat pump and electrolyzer operation

The hourly resolution reveals the dependency between the prices and the operation of heat pumps, electrolysis and fuel cells. Figure 7 depicts hourly electricity and district heating prices, excluding taxes and subsidies (socio-economic costs), for the whole of 2029 in scenario E (reversible electrolysis). While electricity prices are an input to the model, district heating prices are calculated based on the fuel cost, the O&M costs and the heat demand. As Figure 7 shows, the calculated district heating prices are rather stable over the year, slightly decreasing around mid-year, in the hottest months, where only hot water is needed. The reason for this price drop is that the waste incineration plant located in Sønderborg can produce heat more cheaply than other units due to its fuel being free of cost. The electricity spot price varies over the year, with no clear seasonal trend.

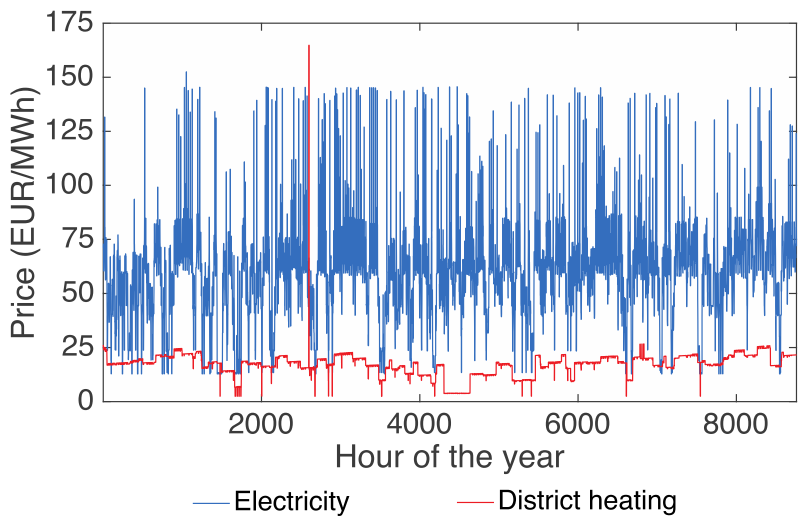


**Figure 7.** Electricity and district heating prices (excl. taxes and subsides) over the year (EUR/MWh).

Figure 8 compares district heating heat pump operation with electricity and district heating prices over hours 720-1440 of the year, corresponding to the month of February. While district heating prices are quite stable in the winter season at around 23 €/MWh, electricity prices vary significantly between

12-150 €/MWh. The feasibility of operating the heat pumps is mainly governed by the electricity price, with the heat pumps being used when the electricity price falls below 70 €/MWh, but ceasing operation when electricity price rises above that value. In scenarios with heat pumps and electric boilers, the fluctuating electricity prices thus have a large and rapid effect on the merit order of the district heating production units in the system.

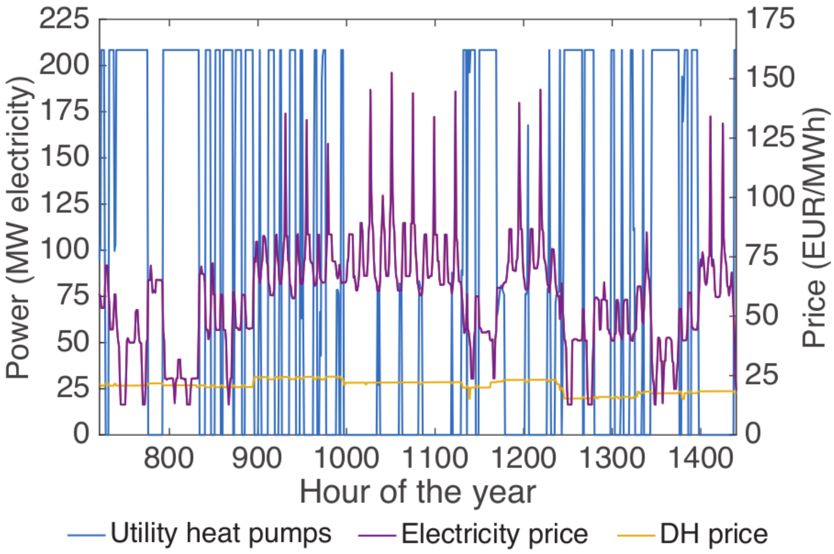


**Figure 8**. Hourly operation of heat pumps in relation to the electricity and district heating prices over February. The input power of the utility heat pumps is shown on the left y-axis, while the electricity and district heating prices are shown on the right y-axis.

A similar effect is observed for the operation of the solid oxide electrolysis and fuel cells. Figure 9 compares the operation of these units with electricity and district heating prices over hours 720-1440 of the year, corresponding to the month of February. The operation of electrolysis and fuel cells is highly dependent on electricity price, with cells running in electrolysis mode in periods of low electricity prices and in fuel cell mode in periods of high electricity prices. It is, however, not possible to identify exact electricity price for cells starting and stopping operation because it also depends on electricity demand and wind and solar production in the given hour. The great dependence of the operation of heat pumps and SOEC/SOFC on the fluctuating electricity price clearly illustrates the need for advanced smart control mechanisms to achieve a cost-efficient operation of the future energy system not only in the model runs, but also in reality.

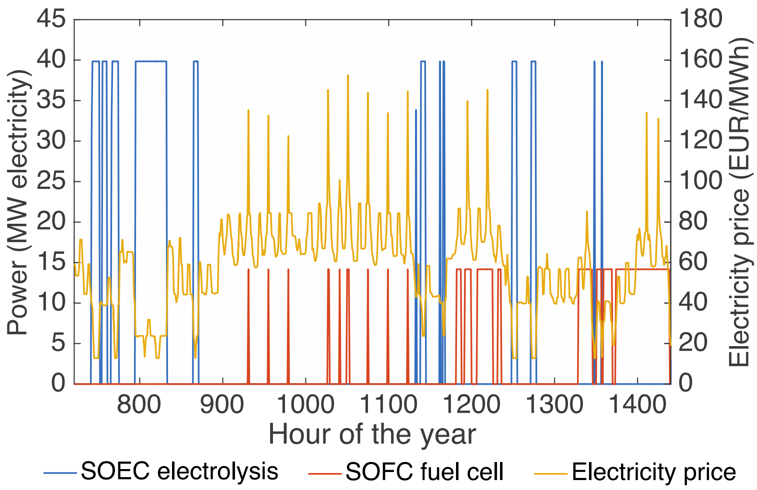


**Figure 9.** Hourly operation of electrolysis and fuel cells in relation to electricity price over the month of February. The input power of the electrolysis cells and the output power of the fuel cells is shown on the left y-axis, while the electricity price is shown on the right y-axis.

## 4.6 Sensitivity analysis

### 4.6.1 Biomass price changes

Figure 10 shows how $CO_2$ emissions and annual system costs change when different biomass prices are implemented in the model. Changing the biomass price does not influence the overall scenario rank order for $CO_2$ emissions, therefore scenarios D and E still perform best on these criteria. However, it slightly affects scenario B, due to its high consumption of biomass. A 30% decrease in the biomass price would cause a 7% drop in $CO_2$ emissions in the case of scenario B. This is caused by the large biomass-fired capacity in scenario B, which enables natural gas and waste production capacity to be replaced with biomass capacity in case of lower biomass prices, thus reducing $CO_2$ emissions. Conversely, other scenarios are not able to change the operation depending on biomass prices, because their biomass-fired production capacity is not as large as in scenario B.

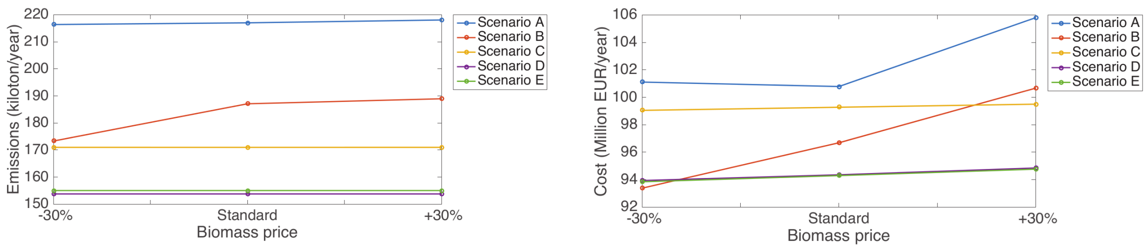


**Figure 10.** Changes in total annual $CO_2$ emissions (left) and total annual system costs (right), depending on the price of biomass.

If biomass prices were to increase, the total annual system costs of scenario A would grow by 5%. In scenario B, a 30% biomass price increase would cause 4% higher system costs, while a 30% biomass price decrease would lower the total annual system costs by 3%, making this scenario the most cost-effective choice in the case of lower biomass prices. This again is because of the high dependency of scenario B on the biomass resource. Thus, as increasing the biomass price by approximately 22% or more influences the overall scenario rank order for $CO_2$ emissions, scenarios D and E would not be feasible in this case.

### 4.6.2 Electricity price changes

Figure 11 depicts how $CO_2$ emissions and annual system costs change when different electricity prices are implemented in the model. Changing the electricity price does not influence the overall scenario rank order for $CO_2$ emissions, so scenarios D and E still perform best on this criterion. In the case of 30% lower electricity prices, 4% lower $CO_2$ emissions in scenarios A, D and E, and 3% lower $CO_2$ emissions in scenarios B and C would occur. 30% higher electricity prices would cause $CO_2$ emissions to rise by 3% in scenario A and by 6% in case of scenarios C, D and E, due to increasing generation from fossil fuels.

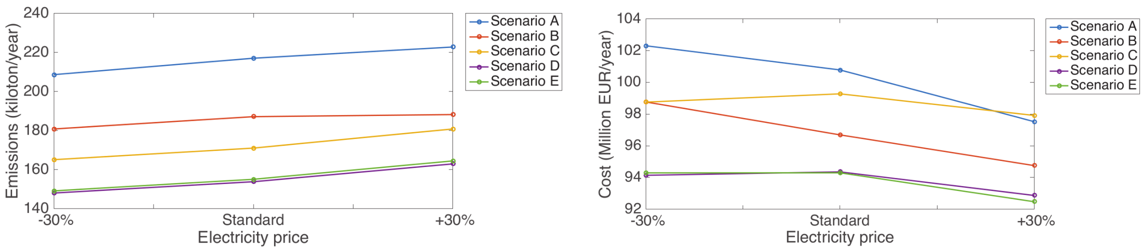


**Figure 11.** Changes in total $CO_2$ emissions (left) and total annual system costs (right), depending on the price of electricity.

Changing the electricity price influences total system costs in all scenarios to some extent, especially scenarios A and B, where electricity exports are the greatest. Sønderborg is a net exporter of electricity in all future scenarios; moreover, the revenue from exported electricity is also higher when the prices are high. The change in system costs is most visible in scenario A: an increase of 30% in the electricity price causes a 3% total system cost reduction.

### 4.6.3 Fossil fuel price changes

Figure 12 shows how $CO_2$ emissions and annual system costs change, when higher and lower fossil fuel prices are implemented in the model. Fossil fuel price changes do not influence $CO_2$ emission levels, because fossil fuel power plants, individual heating and transport are used in the same way irrespective of price of fossil fuels. Besides, the demand for individual heating and transport fuel has to be satisfied even when fuel prices are high.

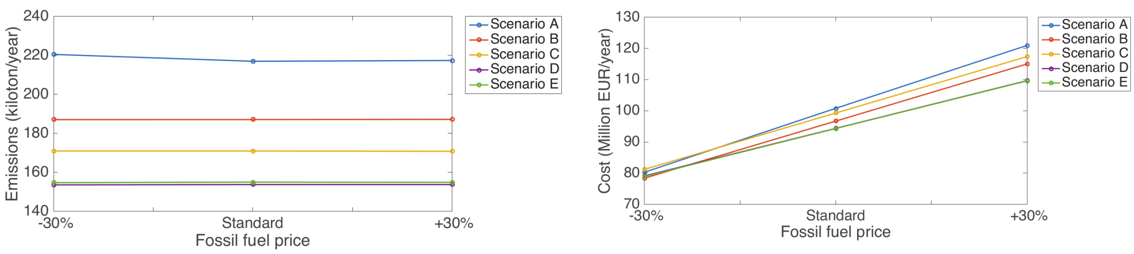


**Figure 12.** Changes in total $CO_2$ emissions (left) and total annual system costs (right), depending on the price of fossil fuels.

The changes in fossil fuel price have a large impact on total system costs. Scenario A results in 20% higher or lower total system costs in the case of fossil fuel price changes, scenario B: 19%, scenario C: 18%, scenario D and E: 16%. Moreover, the scenario rank order changes: with lower fossil prices, scenario B performs best, while with increasing prices, scenario E is more feasible. These cost fluctuations are significant, but clearly scenarios D and E show less dependence on fossil fuel prices, which is a benefit given the unavoidable uncertainty in future prices.

# 5 Discussion

Municipalities are usually not energy system stakeholders as such, but they have a right to influence their energy mix: for example, in Denmark, municipal heat planning projects have to show socio-economic feasibility before being carried out. While the socio-economic perspective does not mirror actual private economic conditions, by excluding changing taxes and subsidies, it does show the viability of the scenarios and indicates that the results are transferable to other countries with different forms of taxation. In reality, to make investments happen, a private-economic analysis would be required from the point of view of customers and investors. Further work could include taxes and subsidies to develop scenarios in private-economic terms.

We have chosen not to rank the scenarios formally by weighting the indicators and calculating an aggregated performance value for each scenario, in order to treat all indicators as equally important. This approach also increases the transferability of our method, as other municipalities could assess their energy scenarios using these indicators. A quantitative analysis could give a more definitive answer to the case at hand, but it would not necessarily lead to more robust conclusions due to the unavoidable arbitrary assumptions behind the weighting factors in such an analysis. The conclusions of this study are therefore rather qualitative in nature, emphasizing general findings that can be used as guidelines in strategic energy system planning in cities globally.

With lower fossil fuel prices, scenario B (biomass) performs best, while with higher fossil fuel prices, scenario E (reversible electrolysis) is most feasible. Given the volatility of fossil fuel prices, the risk of choosing these scenarios is rather high. The biomass scenario would cost the least if biomass prices were to decrease substantially. Taking into consideration developments on the world biomass market, however, this situation is unlikely. The world biomass market, especially for wood pellets, is increasing: for example, in 2013 the EU was responsible for 85% of energy-related global wood pellet consumption [72]. Moreover, Denmark is likely to import a substantial part of its biomass consumption, becoming susceptible to changing global market prices [73]. The situation may be similar in other countries with insufficient biomass resources. In the case of less common technologies, for example electrolysis and fuel cells, the dependence on future energy and climate policies may mean that in the short and middle term the investment costs may stagnate or even slightly increase. These possible volatilities show the importance of a maintaining varied energy system where costs and risks are spread equally among the system elements.

Our results point at electrification as a feasible option for future energy systems. As mentioned in the introduction, no other studies analyzing the application of SOEC or SOFC in a city have been identified. However, considering biomass scarcity, electrolysis was deemed an important element of the future transportation sector in [74] and [21]. Lund [16] has reviewed a body of literature showing the potential of large heat pumps in the Danish energy system and calculated is as being up to 4 GW of thermal capacity. The scenario analyses for a town of Frederikshavn [38] have also found a heat pump suitable for the urban system. Since Denmark is a large wind energy producer, only Danish studies were compared with our results. However, it cannot be excluded that more peer-reviewed work will occur from other regions of the world in the near future, together with increasing share of renewables.

Analyzing benefits of reversible electrolysis in detail could be a topic for further work. For example, the value of the reversibility of the solid oxide electrolysis cell can be quantified as the total cost difference between scenarios D (electrolysis) and E (reversible electrolysis). Scenario E costs approximately 60,000 €/year less than scenario D. The option of operating the electrolyzers reversibly as fuel cells therefore leads to an added value of 1,470 €/MW/year of installed electrolyzer electricity input capacity. Moreover, the addition of reversible electrolysis is useful in balancing supply and demand in the electricity system. This value could be estimated either through comparison with an alternative technology or by analyzing current prices for frequency containment reserve. The alternative technology for reserve capacity could be the cheapest peak power technology, for example natural gas turbines. However, they may not be able to provide the rapid frequency reserve service that reversible electrolysis could. Another approach might be to analyze the capacity payments for electricity system performance markets today. For example, current payments on frequency containment reserve (primary reserve) in Denmark correspond to about 60,000 EUR annually [75]. Although this service is the highest paid, there may be many other suppliers to compete with, and cheaper suppliers may enter the market in the future, so this estimate is uncertain. The potential revenues from such grid services were not taken into account when modelling solid oxide cells in this work.

We assumed that the import of waste can be regulated to match the demand. In Sønderborg in 2014, waste came from both local and imported municipal sources. However, with increasing recycling rates and the new waste incineration plants being built in Europe, waste might become a "scarce resource" in the future. Investigating a scenario, in which importing waste from outside a municipality is forbidden could also be a topic for further studies.

The outcomes of the scenario modelling may also be influenced by the relatively high share of district heating in Sønderborg in 2029: 64% of heat supply, which makes the results less applicable to cities where there is no district heating. However, a system consisting of heat pumps, SOEC and SOFC could also be installed on a neighborhood scale, not requiring an extensive district heating coverage.

In all scenarios, changes in heat consumption caused by, for example, heat savings in the form of improved insulation etc. have been assumed to remain the same as in the municipal plan scenario A, but it could be relevant to assess various shares of heat savings in further work.

Transport and industry remain the main contributors of $CO_2$, and analyzing these sectors in more detail should be emphasized in further work. The future transportation is likely to be highly electrified, but it will almost certainly also require biofuels. It has been suggested that producing biofuels from biomass, waste (via e.g. thermal gasification) and hydrogen (from electrolysis) could be beneficial [13,14] [21][58][76,77]. This work focuses on the use of hydrogen as an input for the fuel cells, for upgrading of biogas to synthetic natural gas and for reforming of syngas to methanol rather than transport fuel, since, according to municipal expectations, transport will be one of the toughest sectors to make sustainable in a short timeframe. Thus, we assume that hydrogen vehicles will not achieve a breakthrough by 2029 and that transport will rather shift towards electricity. However, the possible relevance of hydrogen cars in the remoter future certainly remains open.

# 6 Conclusion

Unlike national governments, many cities around the globe are currently active on the climate action scene, making the topic of local climate mitigation and ways to achieve it extremely relevant. Since Scandinavia is very experienced in local energy planning, we envisage that our results can serve as guidance for the analyzed case and other municipalities.

This article has outlined how the Danish municipality of Sønderborg can approach its $CO_2$ reduction goals by 2029 in five different ways. By constructing and modelling energy scenarios, we investigated the effects of selected energy conversion pathways on the energy system, including total system costs, total energy system efficiency, net system $CO_2$ emissions and total biomass consumption.

While from the private-economic perspective biomass combustion is among the cheapest renewable energy technologies for Danish utilities to invest in at the present time [78], the modelling has demonstrated that a number of other pathways are available if the aim is to achieve low $CO_2$ emissions in a cost-effective way, if local sourcing of biomass is impossible. Nonetheless, these pathways result in different outcomes in environmental and economic terms. Considering all the indicators, scenarios D (electrolysis) and E (reversible electrolysis) are most feasible from a system cost and $CO_2$ emission perspective, while providing substantial biomass consumption savings. Moreover, scenario E shows that the addition of reversible electrolysis actually results in decreased total system cost, even when the benefits of balancing supply and demand in the electricity system are disregarded. The sensitivity analysis has shown that scenarios D and E perform best even if changes are implemented in electricity and fossil fuel prices. Only a drop in biomass prices would make scenario B (biomass) the least costly.

These observations lead to the conclusion that the municipal plan (scenario A) is inferior to the electrified scenarios (C-E) when measured on the indicators selected in this study. We therefore suggest that by considering a greater variety of fuel mixes (with more electrification and novel energy conversion technologies), Sønderborg and similar municipalities design a more energy- and cost-effective energy system while keeping biomass consumption close to the locally available limits and substantially lowering $CO_2$ emissions. Another conclusion is that moving towards an electrified energy system is a better long-term solution than towards a biomass-based energy system. Furthermore, the inclusion of novel and advanced energy conversion pathways such as solid oxide electrolysis and fuel cells, biomass gasification and methanol production help to further decrease the total system costs and $CO_2$ emissions of an electrified energy system. These conclusions hold true for all municipalities and regions with a similar energy demand to Sønderborg and similar amounts of biomass resources relative to the scale of the energy system.

The significance of this study lies in demonstrating that, by complementing combustion with modern energy conversion technologies, it is possible to achieve climate goals cost- and energy-efficiently. Modelling of different conversion technologies applied within all sectors of the municipal energy system enables their feasibility to be assessed, bridging the gap between R&D and implementation. Although solid-oxide electrolysis and fuel cells are used in industry, our results indicate that their application outside of industry is also worth considering as one of the aspects of a sustainable city in the future. If utilities start experimenting with novel energy conversion technologies more often, we expect that new benefits and challenges will be found, further developing the renewable energy industry.

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# Appendix A

**Table A. 1** Economic data for the energy conversion units in the model. The capital expenses for new investments were scaled based on the energy conversion capacity using the following equation for the economies of scale: $c_{scaled} = c_{standard} \left(\frac{P_{scaled}}{P_{standard}}\right)^{\alpha}$, where *c* denote the capital expenses for the standard capacity and the scaled capacity, *P* denote the standard capacity and the scaled capacity and $\alpha$ is the scaling exponent. The exponent takes on values from 0-1 based on how well the capital expenses for each energy conversion technology scale with capacity.

| Conversion unit | Specific CAPEX (€/MW) | Standard capacity (MW) | Scaling exponent | Variable OPEX (€/MWh) | Fixed OPEX (€/MW) | Plant lifetime (years) | Data source |
|---|---|---|---|---|---|---|---|
| Natural gas boilers | 100,000 | 10 | 0.7 | 0.00 | 3,700 | 35 | [61] |
| Biogas boilers | 100,000 | 10 | 0.7 | 3.20 | 3,700 | 35 | [61] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CHP (natural gas) | 600,000 | 100 | 0.7 | 0.00 | 0.00 | 25 | [61] |
| CHP (waste) | 8,500,000 | 75 | 0.7 | 0.00 | 173,170 | 20 | [61] |
| Geothermal + absorption HP | 800,000 | 12 | 0.7 | 5.40 | 0.00 | 20 | [61] |
| Biomass boilers | 800,000 | 12 | 0.7 | 5.40 | 0.00 | 20 | [61] |
| Electric boilers | 75,000 | 10 | 0.7 | 0.50 | 1,100 | 20 | [61] |
| Heat pump (utility) | 575,000 | 5.0 | 0.7 | 2.68 | 3,918 | 20 | [61] |
| Solar heating | 250,512 | 1.0 | 1.0 | 0.57 | 0.00 | 20 | [61] |
| Individual biomass boilers | 642,308 | 0.013 | 1.0 | 0.00 | 2,000 | 20 | [59] |
| Individual electric heating | 800,000 | 0.005 | 1.0 | 0.00 | 10,000 | 30 | [59] |
| Individual gas heaters | 480,000 | 0.013 | 1.0 | 0.00 | 10,800 | 22 | [59] |
| Individual oil heaters | 293,333 | 0.023 | 1.0 | 0.00 | 1,611 | 25 | [59] |
| Individual heat pumps | 1,000,000 | 0.01 | 1.0 | 1.34 | 0.67 | 20 | [59] |
| Photovoltaics | 1,100,000 | 0.9 | 1.0 | 34.00 | 0.00 | 30 | [61] |
| Onshore wind turbines | 1,290,000 | 0.9 | 1.0 | 14.00 | 0.00 | 20 | [61] |
| Offshore wind turbines | 2,430,000 | 5.0 | 1.0 | 19.00 | 0.00 | 25 | [61] |
| SOEC electrolyzers | 590,000 | 5.0 | 0.85 | 0.00 | 15,000 | 20 | [61] |
| SOFC fuel cells | 0 | 0.9 | 0.85 | 0.00 | 2,68 | 20 | [61] |
| Anaerobic digestion | 3,400,000 | 12.3 | 0.7 | 31.00 | 0.00 | 20 | [61] |
| Biogas $CO_2$ removal | 292,950 | 12.0 | 0.7 | 0.00 | 7,324 | 15 | [61] |
| Biogas methanation | 674,748 | 18.9 | 0.7 | 0.00 | 16,869 | 20 | [61] |
| Gasifiers | 555,436 | 100 | 0.7 | 0.00 | 44,435 | 25 | [61] |
| Syngas reformation | 1,884,966 | 100 | 0.7 | 0.00 | 56,549 | 20 | [61] |

**Table A. 2** The energy inputs, outputs and efficiencies (defined as energy outputs divided by the energy inputs) of all electrolysis, fuel cell, gas and liquid fuel production processes that are included in the model. The energy input fractions refer to the energy contents. Lower heating values are used. In the processes that yield heat as a byproduct, the heat is utilized in the district heating network.

| Conversion process | Energy inputs | Energy outputs | Efficiency | References |
|---|---|---|---|---|
| Electrolysis (SOEC) | Electricity (85%)<br>Heat (15%) | Hydrogen | 82% (total) | [57] |
| Fuel cell (SOFC) | Hydrogen (100%) | Electricity<br>Heat | 60% (electricity)<br>95% (total) | [57] |
| Anaerobic digestion | Manure (32.7%)<br>Straw (65.6%)<br>Electricity (1.7%) | Biogas<br>(65% $CH_4$, 35% $CO_2$) | 40% (total) | [61],[79] |
| Biogas CO2 removal | Biogas (93%)<br>Electricity (7%) | SNG | 92% (total) | [61] |
| Biogas upgrade | Biogas (59.4%)<br>Hydrogen (40.6%) | SNG | 91% (total) | [61] |
| Gasification | Wood (40%)<br>Waste (40%)<br>Straw (20%) | Syngas<br>Heat | 82% (syngas)<br>92% (total) | [61] |
| Reformation to methanol | Syngas (100%) | Methanol<br>Heat | 68% (methanol)<br>93% (total) | [80] |

**Table A. 3** The energy inputs and efficiencies for all types of individual heating included in the model. In all cases, the only energy output is heat for space heating and domestic hot water supply.

| Conversion unit | Energy inputs | Efficiency | References |
|---|---|---|---|
| Gas boilers | Natural gas (100%) | 100% | [59] |
| Oil boilers | Heating oil (100%) | 100% | [59] |
| Biomass boilers | Wood (85%)<br>Straw (15%) | 80% (2014)<br>90% (2029) | [59] |
| Electric heating | Electricity (100%) | 99% | [59] |
| Heat pumps | Electricity (100%) | COP 3.0 | [59] |

**Table A. 4** The conversion units for district heating production in the model. The energy inputs, outputs and efficiency of each type of unit are listed.

| Conversion unit | Energy inputs | Energy outputs | Efficiency | References |
|---|---|---|---|---|
| Biomass boilers | Wood<br>Straw | Heat | 100% | [60] |
| Geothermal abs. heat pump + biomass boiler | Geothermal<br>Wood<br>Straw | Heat | 100% | [60] |
| CHP (natural gas) | Natural gas | Heat, electricity | 80% | [60] |
| CHP (waste) | Waste | Heat, electricity | 100% | [60] |
| Natural gas boilers | Natural gas | Heat | 100% | [20] |
| Biogas boilers | Biogas | Heat | 100% | [60] |
| Electric boilers | Electricity | Heat | 100% | [60] |
| Solar heating | Solar energy | Heat | - | [60] |
| Heat pumps | Electricity | Heat | COP 3.0 | [60] |

**Table A. 5** The locally available residual biomass in Sønderborg municipality. For the 2014 scenario, values corresponding to the year 2009 were used, due to lack of more recent data. The values for 2029 are based on a scenario forecast for the availability of biomass for energy purposes in Denmark [81].

| Biomass type | Availability in 2014 (GWh/year) | Availability in 2029 (GWh/year) | Reference |
|---|---|---|---|
| Wood | 39 | 46 | [71] |
| Straw | 207 | 771 | [71] |
| Manure | 180 | 183 | [71] |
| **TOTAL** | **426** | **1,000** | |

**Table A. 6** Electricity and fuel prices used in the model for years 2014 and 2029. The electricity price refers to the Western Danish (DK1) electricity spot price. Time series with an hourly resolution were used as an input for the price of electricity in 2014 and 2029, as well as for the price of fossil fuels in 2014. The 2029 electricity price time series are from a model forecast made by Energinet.dk. In the case of hourly time series, the average price level of the year is shown in parenthesis in the table.

| Fuel | Unit | Price 2014 | Price 2029 | Reference |
|---|---|---|---|---|
| Electricity | €/MWh | 2014 time series (avg. 30.68) | 2029 time series (avg: 58.09) | [64] |
| Wood | €/GJ | 6.68 | 7.71 | [82] |
| Straw | €/GJ | 4.40 | 4.40 | [82] |
| Manure | €/GJ | 2.93 | 2.93 | [83] |
| Natural gas | €/GJ | 2014 time series (avg: 6.11) | 8.82 | [64],[82] |
| Waste | €/GJ | 0 | 0 | [83] |

| | | | | |
|---|---|---|---|---|
| Gasoline | €/GJ | 2014 time series (avg: 22.36) | 34.02 | [84],[82] |
| Diesel | €/GJ | 2014 time series (avg: 21.32) | 30.60 | [84],[82] |
| Heating oil | €/GJ | 2014 time series (avg: 20.65) | 29.64 | [84],[82] |
| $CO_2$ emissions | €/ton | 6.04 | 27.38 | [82] |

**Table A.7** A comparison of fuel consumption for district heating between the model calibration scenario and statistics from 2014.

| **Type** | **Scenario 0** | **Historical data** | **Deviation** | **Data reference** |
|---|---|---|---|---|
| Natural gas | 91.4 | 93.5 | -2.2% | [68] |
| Waste | 218.0 | 212.5 | +2.6% | [68] |
| Wood (including bio-oil) | 128.2 | 123.7 | +3.6% | [68] |
| Straw | 25.4 | 24.4 | +4.1% | [68] |
| Solar energy | 16.6 | 15.7 | +5.7% | [68] |
| Electricity | 5.3 | 10.4 | -49.0% | [68] |
| **Total** | **484.9** | **485.7** | **1.6%** | |

**Table A.8** A comparison of fuel consumption for individual heating between the model calibration scenario and statistics from 2014.

| **Type** | **Scenario 0** | **Historical data** | **Deviation** | **Data reference** |
|---|---|---|---|---|
| Natural gas | 199.2 | 199.4 | -0.1% | [65] |
| Heating oil | 115.1 | 116.1 | -0.9% | [65] |
| Wood | 33.0 | 33.8 | -2.4% | [65] |
| Straw | 6.0 | 6.2 | -3.2% | [65] |
| Heat pumps (thermal output) | 21.0 | 21.2 | -0.9% | [65] |
| Electric heating (thermal output) | 53.0 | 53.5 | -0.4% | [65] |
| **Total** | **427.3** | **430.2** | **-0.7%** | |

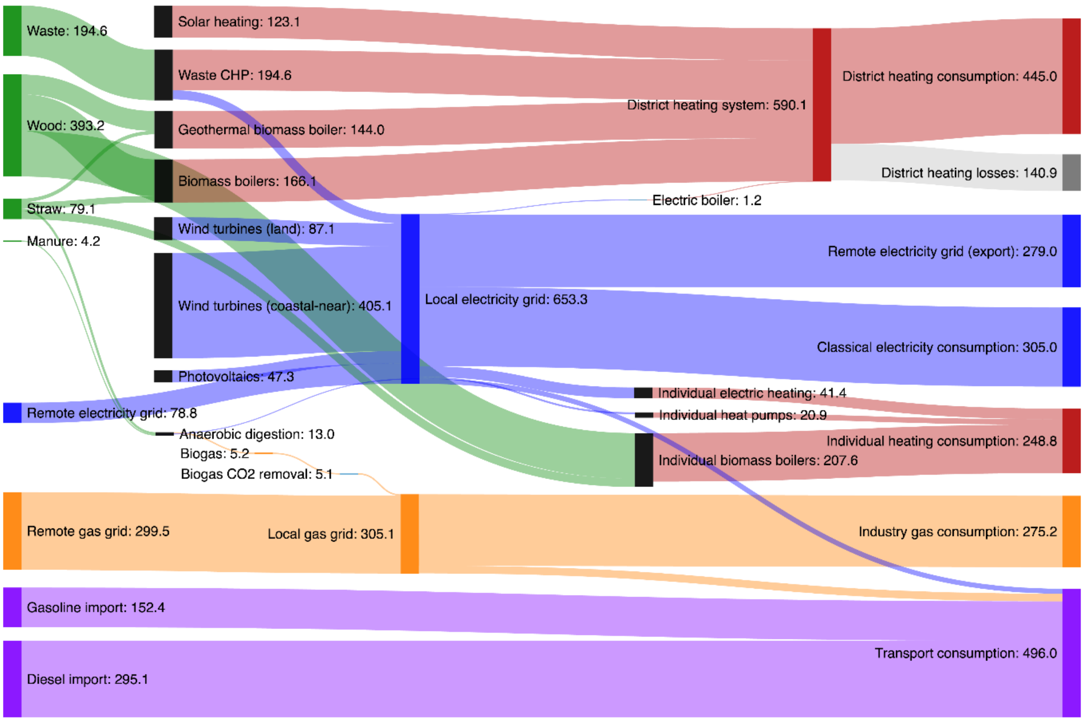


**Figure A.1** Sankey diagram of the model results of the scenario B. The numbers denote the total energy outflow from each node. All numbers in GWh/year.

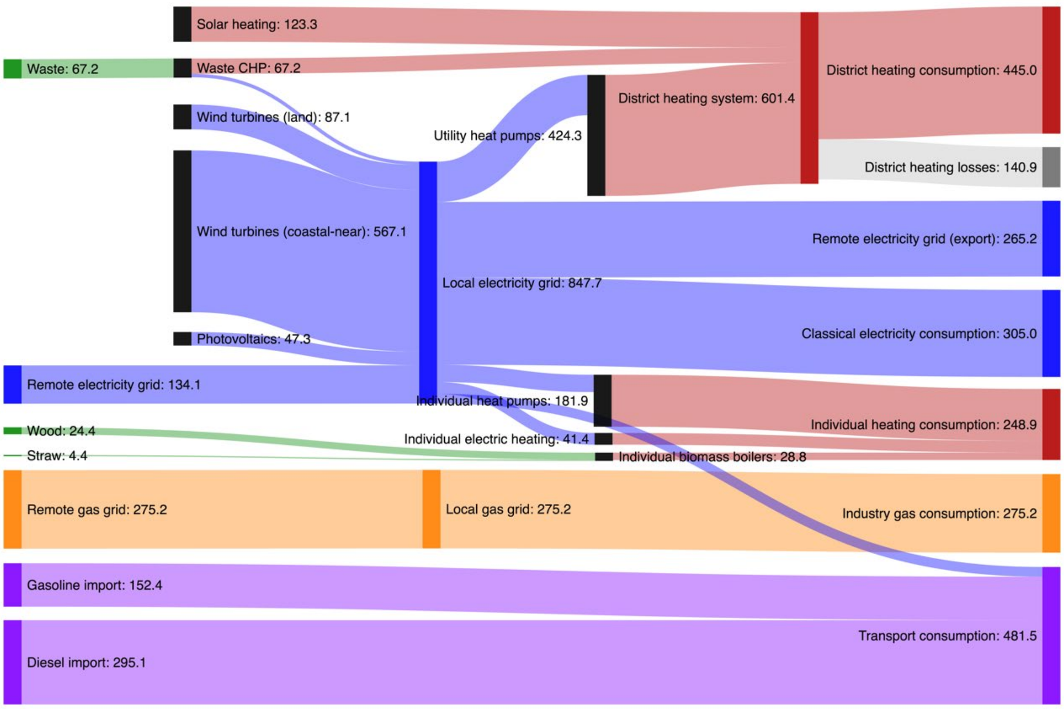


**Figure A.2** Sankey diagram of the model results of the scenario C. The numbers denote the total energy outflow from each node. All numbers in GWh/year.

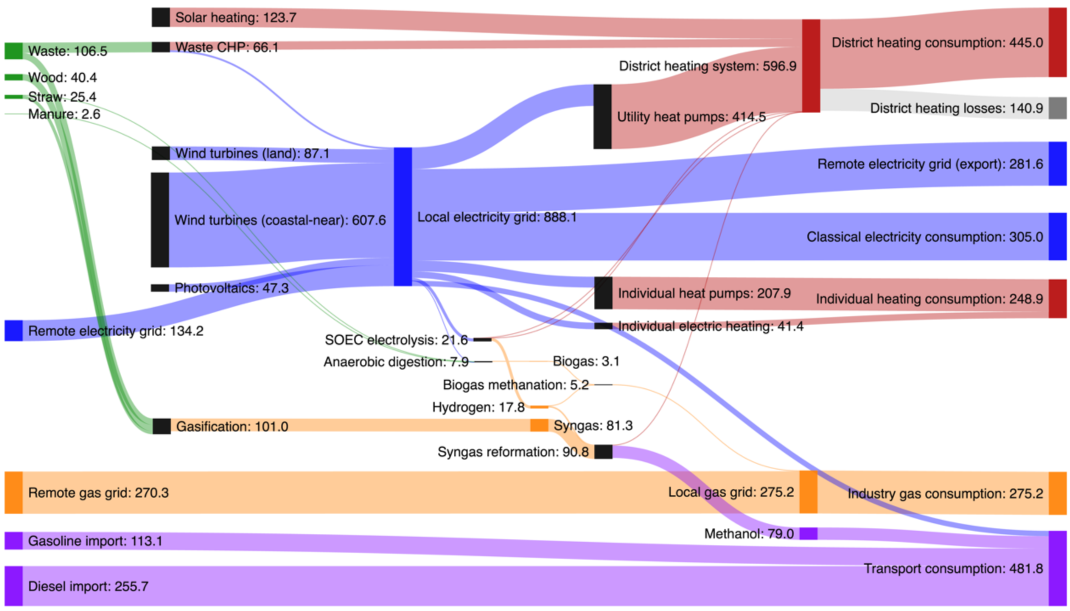


**Figure A.3** Sankey diagram of the model results of the scenario D. The numbers denote the total energy outflow from each node. All numbers in GWh/year.

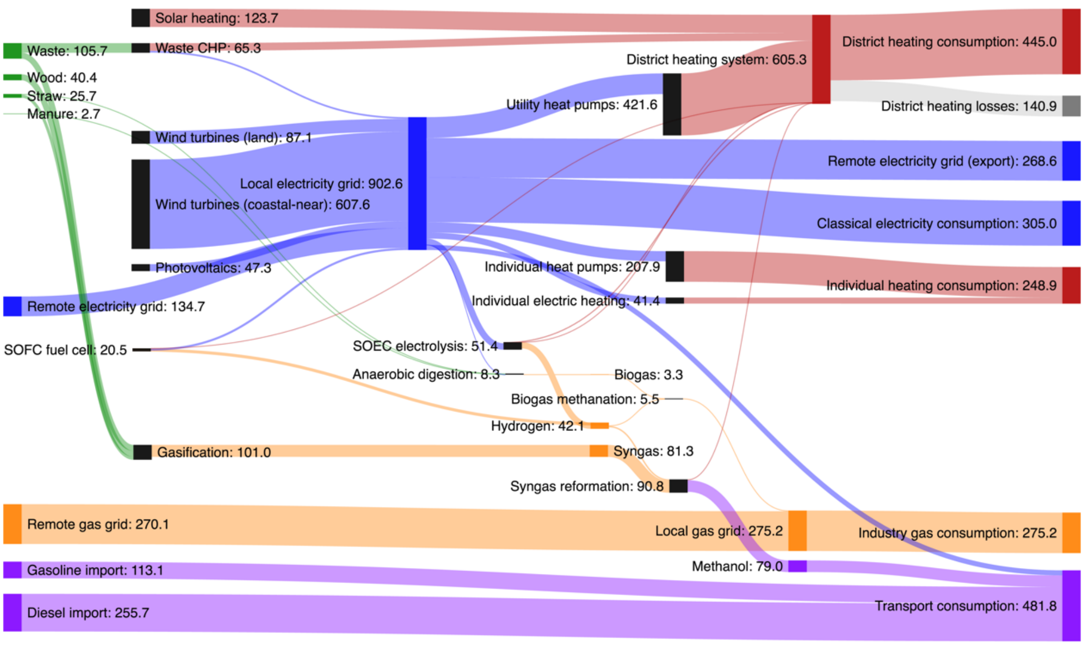


**Figure A.4** Sankey diagram of the model results of the scenario E. The numbers denote the total energy outflow from each node. All numbers in GWh/year.